

Evidence for Shocks as the Origin of Gamma-Ray Flares in Blazars

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We present centimeter-band total flux density and linear polarization light curves illustrating the signature of shocks during radio band outbursts associated in time with γ -ray flares detected by the *Fermi* LAT. The general characteristics of the spectral evolution during these events is well-explained by new radiative transfer simulations incorporating propagating oblique shocks and assuming an initially turbulent magnetic field. This finding supports the idea that oblique shocks in the jet are a viable explanation for activity from the radio to the γ -ray band in at least some γ -ray flares.

1. Overview

Since the mid-1980s, the leading paradigm for the production of flares in AGN in the radio-to-optical bands has been shocks which propagate down the relativistic jets of these sources [1, 2]; hydrodynamical simulations have demonstrated that these structures develop naturally within the jets [3], making this scenario a plausible explanation. In contrast, the location and nature of the emission site giving rise to the GeV γ -ray flares, detected first by EGRET and now by the *Fermi* LAT, have remained contentious issues. While both a site near to the central engine and a location in the parsec scale jet have been discussed in the literature, mounting evidence based on correlated broadband activity (including high resolution VLBA imaging of the inner jet) supports a location within the jet at a site near to the millimeter-band radio core (e.g. [4] and references therein). This result supports a direct relation between the flaring in the radio and in the γ -ray spectral bands and the production of the flaring by the same disturbance. The emitting region itself could take the form of a shock (standing or propagating) or a 'blob' with a chaotic magnetic field where turbulence accelerates the high energy electrons.

The propagating shock scenario, used successfully for the radio band data has now been proposed as a possible explanation for the γ -ray flares in some recent studies, e.g. [5]. However, this hypothesis has not been rigorously tested. Radiative transfer modeling carried out in the mid-to-late 1980s and early 1990s incorporating transverse shocks successfully reproduced the spectral evolution of the total flux density and linear polarization in centimeter-band monitoring data during a few carefully selected radio band events. However, the transverse shock models failed to match the variability in later events in the same sources; there the swings in electric vector position

angle (hereafter EVPA) were through much less than the 90° associated with transverse structures. This discrepancy indicated that theoretical explorations incorporating shocks at other angles to the flow direction were required.

To test whether or not propagating shocks play a significant role in the production of the γ -ray flares, and ultimately to set constraints on the physical conditions in the radio jet during γ -ray flaring, we are monitoring the total flux density and linear polarization at 14.5, 8.0, and 4.8 GHz in a sample of 24 blazars using the University of Michigan 26-m paraboloid (UMRAO), and we are developing new radiative transfer models allowing for oblique shocks for comparison with these data. Results are presented below.

2. Observational Methodology

A specific observational goal of our program during the time period discussed here was to look for the theoretically-expected shock signature in the centimeter-band light curves during γ -ray flares – a swing in the EVPA and associated flaring in the total flux density and linear polarization (LP). The changes in LP result from the compression of an initially tangled magnetic field with the passage of a shock which increases the degree of order. The EVPA, orthogonal to the magnetic field direction in a transparent source, is a direct measure of this magnetic field orientation in the emitting region.

The 24 blazars monitored most intensively during the time period discussed here were 3C 66A, 0235+164, 0420-014, 0454-234, 0528+134, 0716+714, 0727-115, 0805-077, OJ 287, 0906+015, 1156+295, 1222+216, 3C 273, 3C 279, 1329-049, 1502+106, 1510-089, 1633+382, 3C 345, NRAO 530, OT 081,

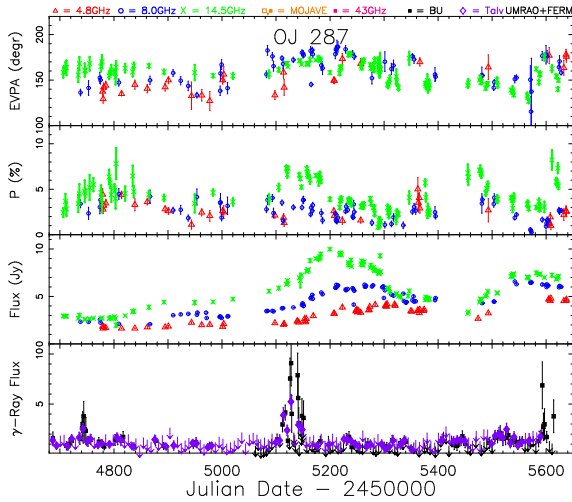


Figure 1: Gamma-ray (bottom) and centimeter band light curves (panels 2-4) at 14.5, 8.0, and 4.8 GHz for the BL Lac object OJ 287. The bottom panel shows the γ -ray light curve ($E > 100$ MeV) obtained using two different binning schemes. Squares denote reductions with a bin size adjusted to the variability state (1 and 5 day binning during flare and non-flare phases respectively). Diamonds denote the light curve generated using 7-day binning throughout. The shorter binning of the data during the γ -ray flare peaks emphasizes the rapidity of the events in the γ -ray band and reveals the complex structure which is smoothed out using the 1-week binning. Units of the γ -ray light curves are 10^{-7} photons/cm²/sec. Panels 2 through 4 show from bottom to top daily averages of the total flux density (S), percentage LP, and EVPA. The symbols denoting the 3 radio band frequencies are indicated in the upper left.

BL Lac, CTA 102, and 3C 454.3. These AGN were chosen for detailed study both because they are bright and variable in the GeV γ -ray band, and because they have exhibited well-resolved flares at centimeter-band in historical monitoring measurements. Additionally, they are all members of the MOJAVE program so that imaging data, useful for disentangling the flux contributions from the individual core and jet components, are available at 15 GHz, an overlapping frequency [6]. Eighteen are members of the Boston University 43 GHz VLBA program (see <http://www.bu.edu/blazars/VLBAproject.html>); these monthly imaging data provide important constraints on the jet emission properties and in combination with the centimeter band monitoring data give information on the opacity between the millimeter core and the 14.5 GHz emission region.

The UMRao observations of the program sources were typically obtained twice per week at 14.5 GHz and once per week at 8.0 and at 4.8 GHz. This cadence was selected to match the expected variability time scales in linear polarization and total flux density in the radio band; it was increased, if required, to track

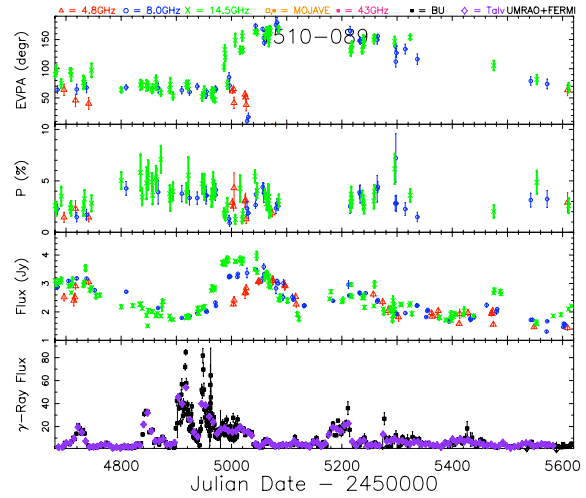


Figure 2: Gamma-ray and centimeter band light curves for the QSO PKS 1510-089. The bottom panel shows the γ -ray light curves generated using two different binning schemes. Squares denote reductions with a bin size adjusted to the variability state (3 days, 1 day and intraday). Diamonds denote the light curve obtained using 7-day binning throughout. The top three panels show daily averages of the centimeter-band total flux density (panel 2) and the linear polarization (panels 3 & 4). Units and symbols are as in Figure 1.

the variations in more detail during individual flares exhibiting relatively rapid flux changes. The sampling rate was highest at 14.5 GHz where the variations are well-documented to be the highest in amplitude and the most rapid. Each daily ‘observation’ consisted of a series of on-off measurements over a 25 to 45 minute time window. These source measurements were interspersed with observations of positionally-nearby calibrators (selected from a grid) every 1 to 2 hours in order to measure the antenna gain and to verify the telescope pointing and instrumental polarization.

2.1. Observational Results

Figures 1 through 3 show examples of the shock signature in the radio band data at or near to times at which large-amplitude flares were detected in the γ -ray band by the *Fermi* LAT for three of our program sources: OJ 287, PKS 1510-089, and OT 081. During these events, swings in EVPA through tens of degrees, increases in fractional LP, and flares in total flux density lasting for a few weeks to a few months were detected. Time delays and reduced amplitudes are apparent at the lowest frequency, 4.8 GHz, characteristic of self-absorption. Specific features to note are: 1) in OJ 287 the two γ -ray flares circa JD 2455110 and 2455580 preceded rises in the fractional LP to levels near 10% and ordered swings through a limited range of about 40° in EVPA. The preceding γ -ray flare near JD 2454740 associated with a millimeter flare (see [7])

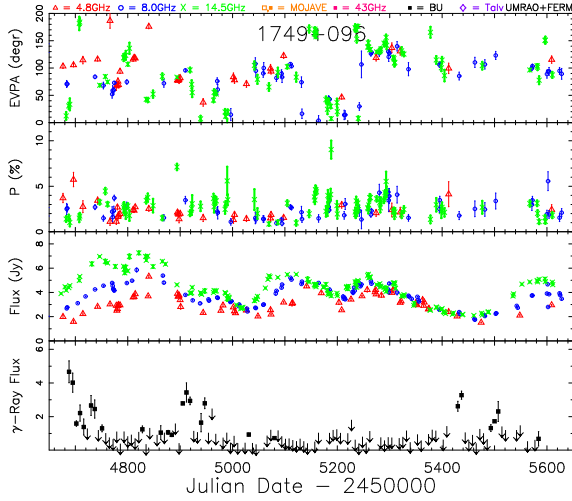


Figure 3: Gamma-ray and centimeter band light curves for OT 81 (1749+096). The bottom panel shows the *Fermi* light curve generated using 7-day binning. Daily averages of the radio band total flux density (panel 2) and the linear polarization (panels 3 & 4) are shown in the top three panels. Several increases in percentage LP and ordered swings in EVPA can be seen, indicating rapid and complex radio-band behavior. Units and symbols are as in Figure 1.

is not resolved in our data. That study argued that the flares analyzed were triggered by the interaction of VLBI-scale components with a standing shock; 2) a series of large amplitude events in the QSO PKS 1510-089 beginning circa JD 2454900 preceded a large flare in total flux density and a swing in EVPA. The broadband behavior is discussed in [8] which attributed flaring to the passage of a knot through a standing conical shock; and 3) complex behavior in the light curves of the BL Lac object OT 81 (1749+096). Radio band flares in this same source during the 1980s were fit with models incorporating a propagating transverse shock (see [9]).

3. The Radiative Transfer Modeling

Support for the shock model as an explanation for the major outbursts seen in single-dish data, and the propagating components seen in maps of parsec-scale flows, as well as support for a shock explanation for at least some *Fermi* events, would come from ‘revalidating’ the ‘shock in jet’ model, by showing that oblique shocks can indeed explain the commonly observed reduced swing in EVPA through only tens of degrees, and associated increases in both percentage LP and total flux density (flares) with the spectral behavior exhibited in the data. To quantitatively test whether the shock scenario can reproduce the features in the data, we have developed radiative transfer models which allow for a shock at any orientation relative

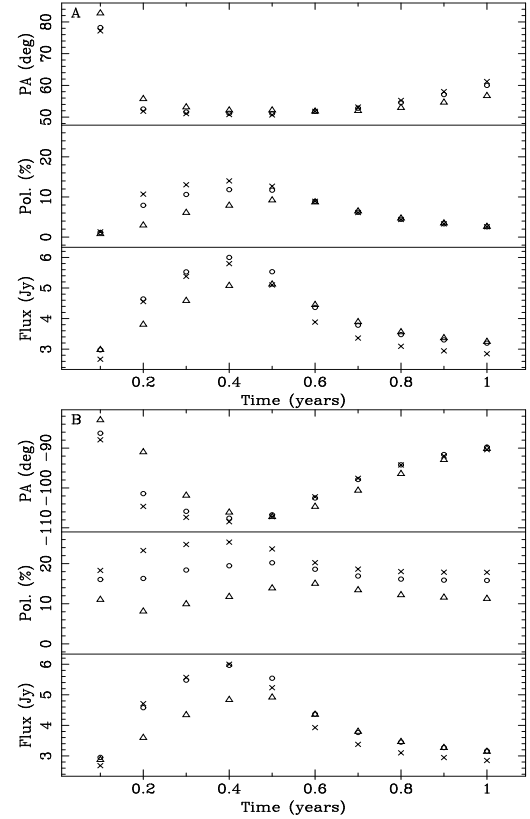


Figure 4: Simulated light curves in total flux density and linear polarization assuming a shock oriented obliquely to the flow direction, Top (A): The magnetic field is assumed to be purely random. Bottom (B): the magnetic field is purely ordered (helical). The symbols correspond to the three UMRAD frequencies shown in Figures 1-3.

to the flow direction. The models discussed here do not allow for retarded time effects which will be included in future modeling. The shock is assumed to propagate at a constant rate (no acceleration or deceleration). A detailed description of the formulation is presented in [10]. Representative simulations illustrating the characteristics of the simulated spectral evolution are shown in Figure 4. Those presented assumed a compression of 0.7, a forward moving shock, a shock obliquity of 45° , and a viewing angle of 10° . As a test of the effect of the magnetic field degree of order on the emission properties and to better understand the jet conditions, light curves were generated assuming a purely ordered (helical) magnetic field, a purely random magnetic field, and a mix of the two. Results are shown for two of these cases: a purely ordered (bottom) and a turbulent (top) magnetic field. Comparison with the data shows that the spectral evolution for the helical case does not match either the

observed maximum fractional LP (the predicted maximum fractional LP $> 20\%$ at 14.5 GHz exceeds the maximum observed value in the UMRAO database of LP observations) or the observed spectral evolution in EVPA. A purely turbulent ambient magnetic field yields the best fit with the data.

4. Summary of Results

The expected shock signature was successfully identified in the radio band data during several *Fermi*-detected events; this result is consistent with a shock-in-jet origin for at least some γ -ray flares. The ordered swings in EVPA typically occurred on timescales of weeks-to-months over a range of tens of degrees. These characteristics and the spectral evolution in linear polarization and total flux density are explained well by our theoretical simulations which incorporate realistic flow conditions. Specific features of the data during radio band outbursts which are reproduced by the new models are: the fractional total flux density increase, the spectral evolution in total flux density through a partially optically thick phase during outburst rise, the magnitude of the peak percentage polarization with opacity/Faraday effects evident at the lowest frequency, and a swing in EVPA through tens of degrees. The effect of differences in the degree of order on the emission have been investigated for the cases of a purely turbulent magnetic field, a purely ordered magnetic field, and a mix of the two. Comparison with the data shows that the observed characteristics are best explained by a model in which the magnetic field within the density enhancement is predominantly random before it passes through the shock.

While detailed light curves were not computed for the standing shock case, we expect that the general characteristics of these light curves will be similar to those for the propagating shock discussed here. The structure of such a feature is unlikely to be simple; at best it will be biconical, and possibly have a Mach stem, and an oblique shock will capture some, but not all, of the attributes of a disturbance passing through the conical structure. Observing and modeling repeated events from the *same* source will be an important next step in pinning down the correct hydrodynamic description of the jets studied and in identifying the origin of the γ -ray emission in specific events.

Acknowledgments

This research was funded by NASA grants NNX09AU16G and NNX10AP16G and by NSF grant

AST-0607523 (University of Michigan), NASA grants NNX08AV65G, NNX08AV61G, NNX08AJ64G, NNX09AT66G, and NNX10AU15G, and NSF grant AST-0907893 (Boston University), and NASA grant NNX08AV67G and NSF grant AST-0807860 (Purdue University). Funding for the operation of UMRAO was provided by the University of Michigan.

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